V lm

(2)

UNITED TECHNOLOGIES
PRATT & WHITNEY

P. O. Box 109600
West Palm Beach, Florida 33410-9600
(407) 796-2000

Government Engines & Space Propulsion

18 November 1991

Office of Navy Research
Scientific Officer
Attn: Dr. A. K. Vasudevan, Code 1216
Contract No. N00014-91-C-0124
Item No. 0002, Sequence No. A001
800 N. Quincy Street
Arlington, Va 22217-5000

Subject: Submittal of the Progress Report, FR21998-1

Gentlemen:

In accordance with the applicable requirements of the contract, we herewith submit one (1) copy of the subject report.

Very truly yours,

UNITED TECHNOLOGIES CORPORATION
Pratt & Whitney

Margaret B Hall

Margaret B. Hall
Contract Data Coordinator

cc: With Enclosures

Director, Naval Research, Code 2627
DPRO
Defense Technical Information Center (2 copies)

FR2198-01 15 November 1991

FATIGUE IN SINGLE CRYSTAL NICKEL SUPERALLOYS

Technical Progress Report

Charles Annis
Program Manager

UNITED TECHNOLOGIES PRATT&WHITNEY
P.O. Box 109600
West Palm Beach, FL 33410-9600
(407)796-6565
Government Engines and Space Propulsion

15 November, 1991

Period of performance
16 September 1991 through 15 November 1991

Contract N00014-91-C-0124

Statement A per telecom
Dr. A. K. Vasudevan
ONR/Code 1222
Arlington, VA 22217-5000
NWW 12/2/91

Prepared for:

Dr. A. K. Vasudevan, Scientific Officer
Office of Naval Research
Department of the Navy
800 N. Quincy Street
Arlington, Va 22217-5000

I. Introduction and Program Objective

This program investigates the seemingly unusual behavior of single crystal airfoil materials. The fatigue initiation processes in single crystal (SC) materials are significantly more complicated and involved than fatigue initiation and subsquent behavior of a (single) macrocrack in conventional, isotropic, materials. To understand these differences it is helpful to review the evolution of high temperature airfoils.

Characteristics of Single Crystal Materials

Modern gas turbine flight propulsion systems employ single crystal materials for turbine airfoil applications because of their superior performance in resisting creep, oxidation, and thermal mechanical fatigue (TMF). These properties have been achieved by composition and alloying, of course, but also by appropriate crystal orientation and associated anisotropy.

Early aeroengine turbine blade and vane materials were conventionally cast, equiaxed alloys, such as IN100 and Rene'80. This changed in the late 1960s with the introduction of directionally-solidified (DS) MAR-M200+Hf airfoils. The DS process produces a <001> crystallographic orientation, which in superalloys exhibits excellent strain controlled fatigue resistance due to its low elastic modulus. The absence of transverse grain boundaries, a 60% reduction in longitudinal modulus compared with equiaxed grains, and its corresponding improved resistance to thermal fatigue and creep, permitted significant increases in allowable metal temperatures and blade stresses. Still further progress was achieved in the mid-1970s with the development of single crystal airfoils[1].

The first such material, PWA 1480, has a considerably simpler composition than preceding cast nickel blade alloys because, in the absence of grain boundaries, no grain boundary strengthening elements are required. Deleting these grain boundary strengtheners, which are also melting point depressants, increased the incipient melt temperature. This, in turn, allowed nearly complete γ' solutioning during heat treatment and thus a reduction in dendritic segregation. The absence of grain boundaries, the opportunity for full solution heat treatment, and the minimal post-heat treat dendritic segregation, result in significantly improved properties as compared with conventionally cast or directionally solidified alloys. Single crystal castings also share with DS alloys the <001> crystal orientation, along with the benefits of the resulting low modulus in the longitudinal direction.

Pratt & Whitney has developed numerous single crystal materials. Like most, PWA 1480 and PWA 1484 are γ' strengthened cast mono grain nickel superalloys based on the Ni-Cr-Al system. The bulk of the microstructure consists of approximately 60% by volume of cuboidal γ' precipitates in a γ matrix. The precipitate ranges from 0.35 to 0.5 microns and is an ordered Face Centered

---

[1] Gell, M., D. N. Duhl, and A. F. Giamei, 1980, "The Development of Single Crystal Superalloy Turbine Blades," *Superalloys* 1980, proceedings of the Fourth International Symposium on Superalloys, American Society for Metals, Metals Park, Ohio, pp. 205-214.

Cubic (FCC) nickel aluminide compound. The macrostructure of these materials is characterized by parallel continuous primary dendrites spanning the casting without interruption in the direction of solidification. Secondary dendrite arms (perpendicular to solidification) define the interdendritic spacing. Solidification for both primary and secondary dendrite arms proceeds in <001> type crystallographic directions. Undissolved eutectic pools and associated microporosity reside throughout the interdendritic areas. These features act as microstuctural discontinuities, and often exert a controlling influence on the fatigue initiation behavior of the alloy. Also, since the eutectics are structurally dissimilar from the surrounding matrix their fracture characteristics will differ.

Single Crystal Fatigue

The fatigue process in single crystal airfoil materials is a remarkably complex and interesting process. In cast single crystal nickel alloys, two basic fracture modes, crystallographic and non-crystallographic, are seen in combination. They occur in varying proportions depending upon temperature and stress state. Crystallographic orientation with respect to applied load also affects the proportion of each and influences the specific crystallographic planes and slip directions involved. Mixed mode fracture is observed under monotonic as well as cyclic conditions.

Single crystal turbine blades are cast such that the radial axis of the component is essentially coincident with the <001> crystallographic direction which is the direction of solidification. Crystallographic fracture is usually seen as either octahedral along multiple (111) planes or under certain circumstances as (001) cleavage along cubic planes. The fatigue and fracture processes can be visualized by relating the fractographic features to structural aspects of the alloy system. In Figure 1 the FCC unit cell structure is shown along with a depiction of the (111) crystallographic plane. Such planes in eight neighboring unit cells describe an octahedron. The fracture in Figure 2 displays prominent (111) octrahedral shear planes.

Non-crystallographic fracture is also observed. Low temperatures favor crystallographic fracture. At higher temperatures, in the 427C range, small amounts of non-crystallographic propagation have the appearance of Stage II transgranular fatigue in a related fine grain equiaxed alloy. Under some conditions, this propagation changes almost immediately to the highly crystallographic mode along (111) shear planes, frequently exhibiting prominent striations emanating from the fatigue origin and continuing to the final fracture region. Under other conditions the non-crystallographic behavior can continue until global failure occurs, as is seen in Figure 3. At intermediate temperatures (around 760C) non-crystallographic propagation is more pronounced and may continue until tensile overload along (111) planes occurs, or may transition to subcritical crystallographic propagation. At 982C propagation is almost entirely noncrystallographic, similar to Stage II transgranular propagation in a polycrystal.

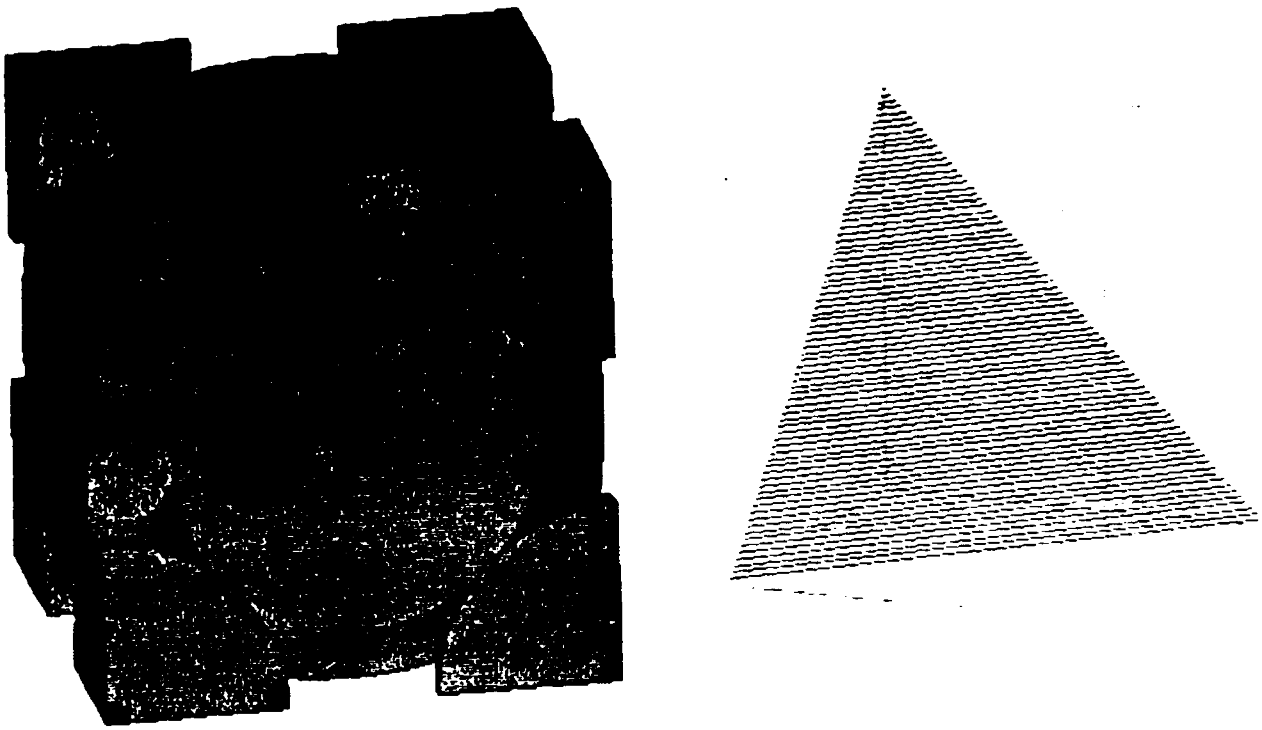

Figure 1. The FCC unit cell and the (111) plane: Crystallographic fracture frequently occurs parallel to the (111) plane in single crystal alloys.

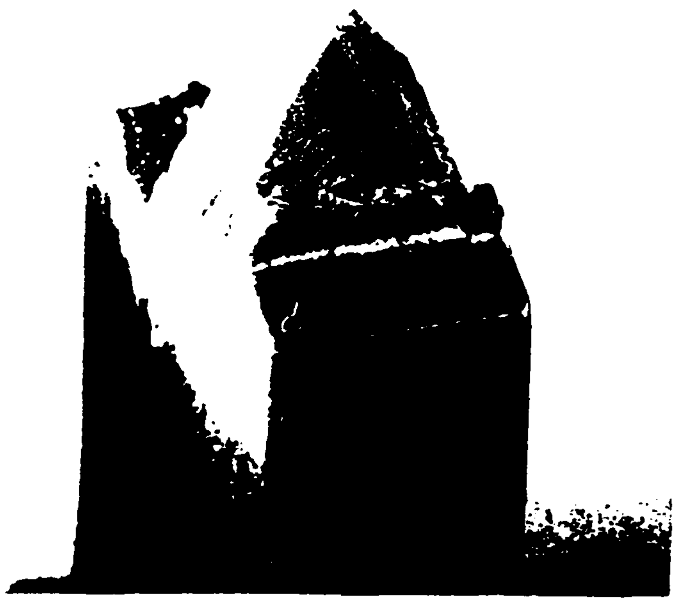

Figure 2. Notched 1100F LCF fracture (PWA 1484 + HIP): Prominent (111) octahedral shear planes frequently [illegible] Fatigue [illegible]

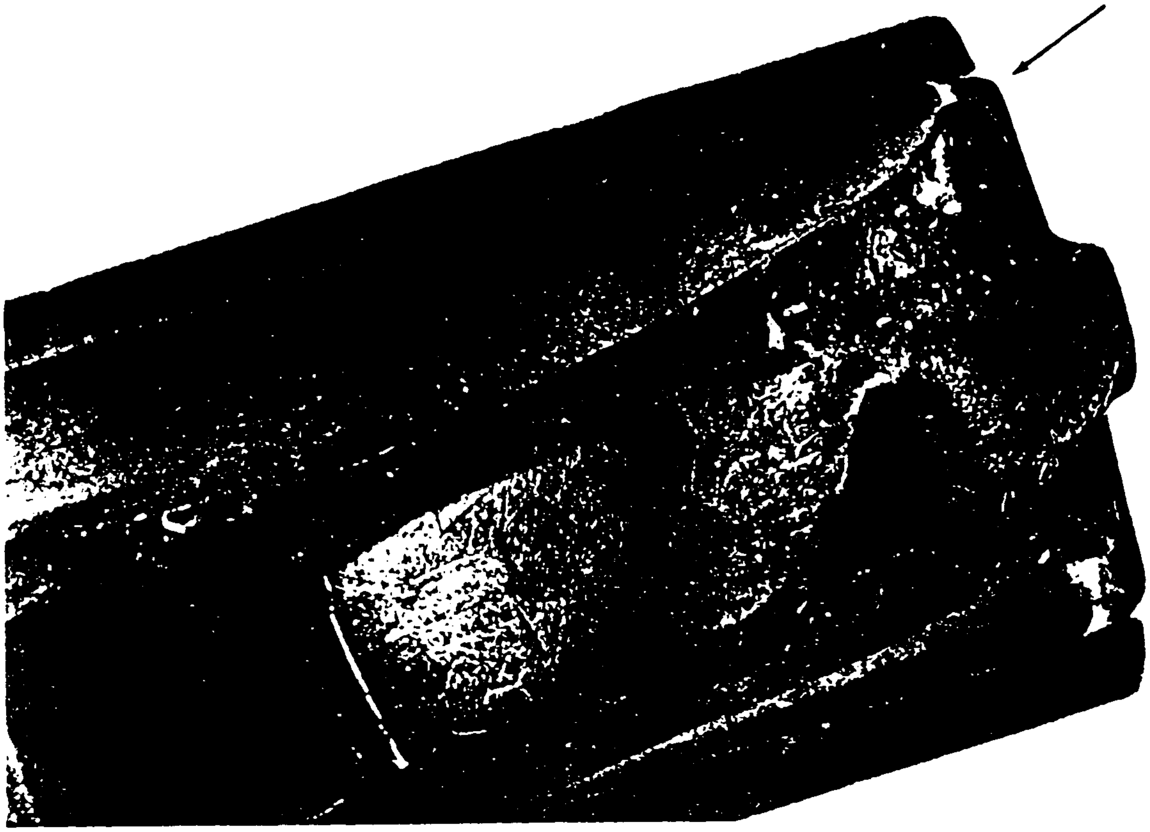

Figure 3. **Noncrystallographic transprecipitate Fracture:** Such failure can occur normal to the principal loading axis at elevated temperatures and lower stresses.

Damage Catalogue

This program will identify and compile descriptions of the fracture morphologies observed in SC airfoil materials under various combinations of temperature and stress associated with advanced Navy aeropropulsion systems. We will suggest fatigue mechanisms for these morphologies and catalogue them as unique damage *states*. Most testing will be accomplished under ancillary funding, and therefore be available to this effort at not cost. The work is oranized into four tasks, which are described in the following paragraphs.

II. Program Organization

The program is structured into four tasks, three technical and one reporting. The individual tasks are outlined here.

Task 100 - Micromechanical Characterization

This task will define the mechanisms of damage accumulation for the various types of fracture observed in single crystal alloys. These fracture characteristics will be used to establish a series of Damage States which represent the fatigue

damage process. The basis for this investigation will be detailed fractographic assessment of failed laboratory specimens generated in concurrent programs. Emphasis will be on specifically identifying the micromechanical damage mechanisms, relating them to a damage state, and determining the conditions required to transition to an alternate state.

Task 200 - Analytical Parameter Development

This task will extend current methods of fatigue and fracture mechanics analysis to account for microstructural complexities inherent in single crystal alloys. This will be accomplished through the development of flexible correlative parameters which can be used to evaluate the crack growth characteristics of a particular damage state. The proposed analyses will employ the finite element and the hybrid Surface-Integral and Finite Element (SAFE) methods to describe the micromechanics of crack propagation.

Task 300 - Probabilistic Modeling

This task will model the accumulation of fatigue damage in single crystal alloys as a Markov process. The probabilities of damage progressing between the damage states defined in Task 100 will be evaluated for input into the Markov model. The relationship between these transition probabilities and fatigue life will then be exploited to establish a model with comprehensive life predictive capabilities.

Task 400 - Reporting

Running concurrently with the analytical portions of the program, this task will apprise the Navy Program Manager and Contracting Officer of the technical and fiscal status of the program through R&D status reports.

III. Technical Progress

Because of unavoidable delays, the actual program authorization did not become operational until 1 October, 1991, although the contract's effective date is 16 September. We are confident that this will have no lasting influence on the timely and successful execution of this contract.

Internal program management tools are in-place and operational, providing weekly summaries of all person-hours worked and technical progress by task and functional group. Organizational meetings were conducted to review the responsibilities of the individual technical contributors, and to establish interim, internal technical milestones. Although not required by the contract document, regular monthly technical progress reports will be provided to the Navy program management. The purpose of these (frequent) reports is two-fold:
1. Establish internal reporting and analysis discipline so that potential difficulties are discovered and dealt with in the most expeditious and timely fashion.
2. Provide internal documentation of technical progress.

Fractographic analysis to identify micromechanical indicators of state transitions and the underlying dislocation behavior is underway.

IV. Current Problems

No technical problems have been encountered during the reporting period.